Next Generation Wearable Haptics Should Balance Virtual & Real-world Fidelity

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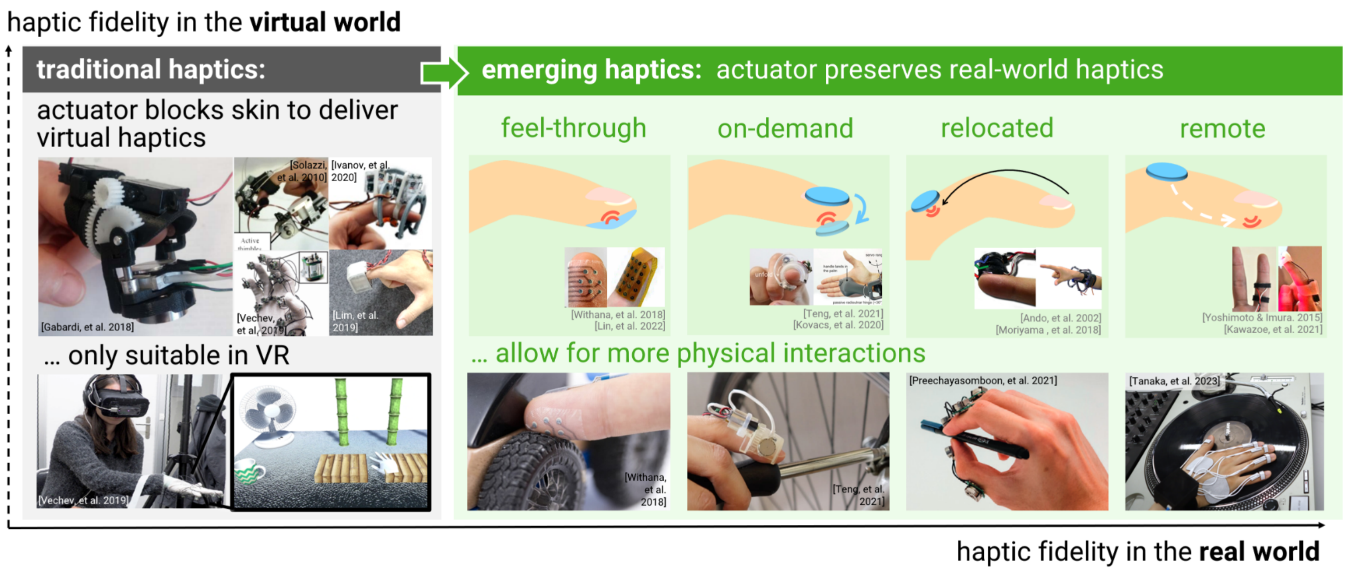

Figure 1: We argue that HCI should move away from the quality of a "virtual sensation" as the key metric to judge the efficacy of a wearable haptic interface for the fingerpad. Instead, we argue for an emergent trend to consider not only the rendering of virtual sensations but also *how the haptic device blocks real-world sensations* when users need to interact with real-world objects (e.g., as they type, use tools, put on a headset, shake someone's hands). We reason that considering these two parameters simultaneously will enable a new generation of tactile wearable devices that *balance* two forms of haptic fidelity: the fidelity of the sensation from both the virtual and the real world. Ultimately, this balancing act will enable new domains for haptics, not possible today, such as seamlessly switching between virtual training and real-world tasks (Image credits: left column "traditional haptics" from [46, 65, 94, 143, 165] and the right column "emerging haptics" from [12, 79, 87, 96, 109, 128, 149, 154, 174, 186]). Figures from publications reproduced with permission from their respective copyright holders or licenses.

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Abstract

Providing tactile-feedback when users contact virtual-interfaces has been a seminal advance. However, we posit these advances have been explored in *isolation* from considerations of users' *physical* interactions with surrounding-objects. Most touch-interfaces were designed to *optimize virtual interfaces*, but rarely consider that users also need to feel *physical* interfaces (e.g., tools, putting on/off headsets). We argue against this being the sole design-objective driving haptic-interfaces; instead, we propose also to optimize *the fidelity of the real-world sensations* that users feel while wearing a haptic device. We propose a framework to classify touch-devices by measuring not only their abilities to deliver virtual-feedback but also how much they impair physical-feedback—we argue this balancing act is an urgent mainstream need, given the success of Mixed-Reality. Thus, to accelerate the research in this area, we synthesize existing techniques into new conceptual-categories: feel-through, on-demand, relocated, and remote actuators. Finally, we present their pros/cons and discuss a possible roadmap.

CCS Concepts

• **Human-centered computing**; • **Haptic devices**;

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1 Introduction

The addition of tactile feedback to touch-based interactions, in Virtual Reality/Mixed Reality (VR/MR/XR) user interfaces, has been a key advancement over the last few decades. Actuators that deliver tactile haptics allow users to feel when they contact a virtual surface, be it clicking a button on a flat touchscreen or feeling the texture of an object in Virtual Reality. These devices have proved useful in many settings, e.g., physical skill training [160], remote operation [159], and entertainment [170]. With key advancements in mainstream XR in the past years, including devices now available off the shelf, wearable tactile devices have the potential to enter everyday interactions, e.g., always-available sensory experiences that feel realistic and personalized. This has accelerated research in wearable haptics [121, 125].

Most of the tactile interfaces in the state-of-the-art were designed with the primary *goal of optimizing the haptic sensations that the device communicates to the user* when the user touches a virtual interface. The devices were developed to deliver rich sensations by integrating many haptic modalities (vibration, pressure, and temperature, etc.). These are useful for simulating realistic objects and environments (VR/teleoperation). Notably, as more actuators are added to the device to increase realism, they become larger and heavier.

However, as exciting as these advances are, we argue they have largely been explored in *isolation* from considerations of users' *physical* interactions in the real world. These interfaces are typically designed and tested in controlled environments such as laboratories, without considering the user's physical interactions with other objects around them that are not part of the laboratory task or part of the user interface itself. These haptic devices, despite being wearable, hinder the user's perception of the physical world because the haptic actuators obstruct body parts used to sense other physical objects. In fact, many of these devices impede manual dexterity and physical interactions with the surrounding environment, including grasping objects, using tools, shaking someone's hand, or even simply putting on and taking off the VR headset (e.g., requiring another person to do it for the user). As a result, the use of haptic devices is limited to highly specialized settings.

We posit that this is a key missed opportunity for Human-Computer Interaction (HCI). In the last few decades, as computing interfaces have become more miniaturized [112] and woven into the fabric of everyday life [100], we continuously use computers of different form factors throughout the day (PC, mobile phones, smartwatches, etc.), multitasking and switching contexts rapidly and frequently. As more immersive media like VR/XR become mainstream, the need for realistic haptic devices grows. In fact, we argue that Mixed Reality (MR) presents a compelling case where a haptic device can only be successful if it enables smooth *switching* between feeling the virtual world and the physical world. This presents a major challenge for tactile haptic devices, as most existing devices cannot support switching from touching virtual objects to touching real objects—**most actuators cover up the user's skin and do not let users feel the real world, which impairs their tactile sensitivity and consequently their manual dexterity.** The starkest example of this is that of glove-based haptic devices, which have seen a huge increase in popularity in both research [121] and industry [34].

We identified several key works ([12, 16, 54, 79, 126, 149, 154, 174]—and other more in the paper), which we argue can serve as a *counter-argument* to this traditional goal of haptics (i.e., *optimize virtual haptics*); mainly, since these works are motivated by aiming for haptic interactions in the *real world.* While, on the surface, these new emergent ideas propose very distinct haptic techniques, we believe they share similar goals that can be *synthesized into haptic strategies*, namely: *feel-through, on-demand, relocated,* and *remote actuators.* Inspired by these individual works, we propose a framework to classify haptic devices by measuring not only their abilities to deliver virtual feedback but also *how much they impair physical feedback* in the real world (Figure 1)—we argue this balancing act is an urgent mainstream need, given the success of XR. We present their pros/cons and discuss a possible roadmap. We highlight an important emerging direction and hope to inspire researchers to envision balanced future interactions between the virtual and the real world.

2 Contribution & Limitations

This is not a typical survey-based paper but rather one that robustly puts forward a *challenge* for our field. Our contribution includes: (1) articulating an emerging direction in the field that is currently scattered in individual prior work; (2) categorizing and summarizing major strategies these challenges, leading to a holistic understanding; and (3) discussing future roadmaps that might assist the next generation of HCI researchers in developing new haptic devices for more balanced interactions between the virtual and physical world.

As with any argumentative-based proposal, ours is not without limitations: (1) we focus on contact-based wearable haptics, while other devices (e.g., robotic devices or non-contact haptics) may be of interest of investigation, as they pose other unique challenges; and (2) we focus solely on *tactile* feedback, mostly for the hands (most common type of wearable haptics [121]), which is the case where these research challenges manifest most severely.

3 Related work

To best understand how we arrived at this position in which most of wearable haptics research is not designed with the goal of letting users interact freely with their surroundings, we discuss the main driving forces throughout the last decades of this interactive field, from teleoperation, training simulation, to wearable-VR/MR.

3.1 Teleoperation as the driver for stationary haptics

Teleoperation or training simulations have been a main driver for haptics since the 1980s [21]. Here, the addition of haptics enabled more precise manipulation with fewer errors [53, 62, 180]. The goal is to *faithfully* represent the sensations from sensors to enable precise control of robots remotely (e.g., a robotic arm manipulating hazardous materials), or simulate a scenario where performance is highly dependent on physical properties of the simulated environment (e.g., surgery with simulated tissues). These earlier haptic devices were typically stationary setups in which a user looked through a stereoscopic display (a precursor to modern VR/AR headsets). In these setups, the user's hands typically hold onto the controllers (sometimes dubbed as manipulators) that provide corresponding force and tactile feedback of the remote endpoint (e.g., the forces sensed by a robotic gripper's end-effector when grasping an object).

3.2 Rise of wearable tactile haptics

Since the early 2010s, the advancement of mainstream wearable VR headsets has brought forward a wave of immersive audiovisual experiences, in which users are no longer tethered to stationary setups and, instead, are able to freely walk around in their surroundings [61, 130]. This untethered ability has proven successful for head-mounted computing—more than a decade later, the availability of these wearable devices has permeated the mainstream, with several fully untethered HMDs reaching millions of users worldwide [90]. With widespread interest, the applications of HMD are also expanding, beyond the early visions for teleoperation, and now include gaming (VR's largest market [90]), interior design [168], heritage preservation [101], museum experiences [26], and health/exercise [25]—just to cite a few.

The most typical approach to interacting in VR/XR is to use handheld controllers or free-hand gestures. Controllers typically offer 6-DOF tracking and haptic feedback (mostly vibrotactile). Controllers are especially suitable for interactions mediated with a tool (e.g., a virtual drill). Free-hand gestures, typically tracked via head-mounted cameras, provide a wider array of options, not just 6-DOF from the hand's position (as with a controller), but also dexterous movements (e.g., finger taps, finger pinches, grasps, and so forth), or even full-body movements (e.g., legs, torso, and so forth). Additionally, the use of free-hand gestures rather than holding controllers enabled users to switch tasks seamlessly, like typing with all fingers, holding a prop, etc. Following the success of free-hand interactions in VR/XR (i.e., available out-of-the-box in most mainstream headsets), many turned to converting haptic devices into wearables to provide sensations (e.g., contact, textures, etc.) whenever the user touches virtual objects with their body [121, 125].

3.3 Wearable haptics for VR realism

For a wearable device to generate realistic feedback onto our skin's touch receptors, it needs to be able to physically send signals to our skin—for most devices, these signals are mechanical (i.e., real pressure, real touch, etc.).

As such, the wearable device needs to sit atop the area it is meant to stimulate, as depicted in Figure 2 (a). This is why, for the most popular target, hands/fingers, wearable tactile devices are typically engineered as gloves or thimbles. In other words, haptic devices are designed to physically *wrap* our bodies into this simulated world as much as possible. For instance, a vibration glove [6] is very much like an ordinary glove, except it also has vibration motors in contact with the user's fingerpads and palm. Therefore, a user wearing such a glove can touch a virtual object and feel the corresponding motor under their fingerpad vibrating. To keep the motors in the right place, the glove wraps these motors tightly around the user's skin. With this approach, sensations can be rendered at the right locations no matter how the user moves. The benefit of wearables is that feedback can be provided wherever the user goes, aligning with the untethered usage that VR headsets provide. Exemplar devices and applications are shown in Figure 2 (b)(c).

Besides vibrations, our skin contains receptors that respond to diverse stimuli, for example: mechanoreceptors (vibrations, pressure, skin deformation), thermoreceptors (temperature), but also chemoreceptors or nociceptors, which are less explored in haptics [33, 72, 132]. Typically, a single actuator can only render a limited range of what we can sense; for example, vibration devices cannot produce a cold sensation. Thus, many have proposed multimodal devices that use combinations of actuators to produce more diverse sensations. As an unfortunate result, multimodal haptic devices tend to be more cumbersome. For example, the common vibration motor used in phones (LRA) has a resonant frequency at about 170 Hz, yet the vibration range that we can feel is wider than that [72]. Wide-band vibration actuators exist, but as they typically require combining two motors [92] (imagine 21 g mounted on one finger), and result in larger devices. For generating pressure and skin deformation (e.g., for simulating grasping a weight, which drags and deforms the fingerpads), other types of actuators are developed, typically a combination of motors and mechanical linkages. The complexity and size of these devices are often related to their ability to render feedback, e.g., degrees of freedom, force output, etc [64, 141]. This effect is also seen for other approaches, like temperature feedback, which is typically realized using Peltier elements [46] (45.7 g on one finger), combined with fans and heatsinks that are often too bulky [102]. From these examples, we can observe that while combining various haptic actuators achieves more tactile sensations, it results in a more cumbersome wearable (even assuming the mechanisms for target haptic feedback are compatible, which is not always the case).

4 Illustrating the traditional haptics approach

The recent trend of Mixed/Augmented Reality (MR/AR), where the user's interactions involve physical tools and the physical world, conflicts with the traditional insights we developed over decades of haptics in teleoperation and early-VR. Moreover, as haptic devices become more advanced/multimodal, they will create more conflicts

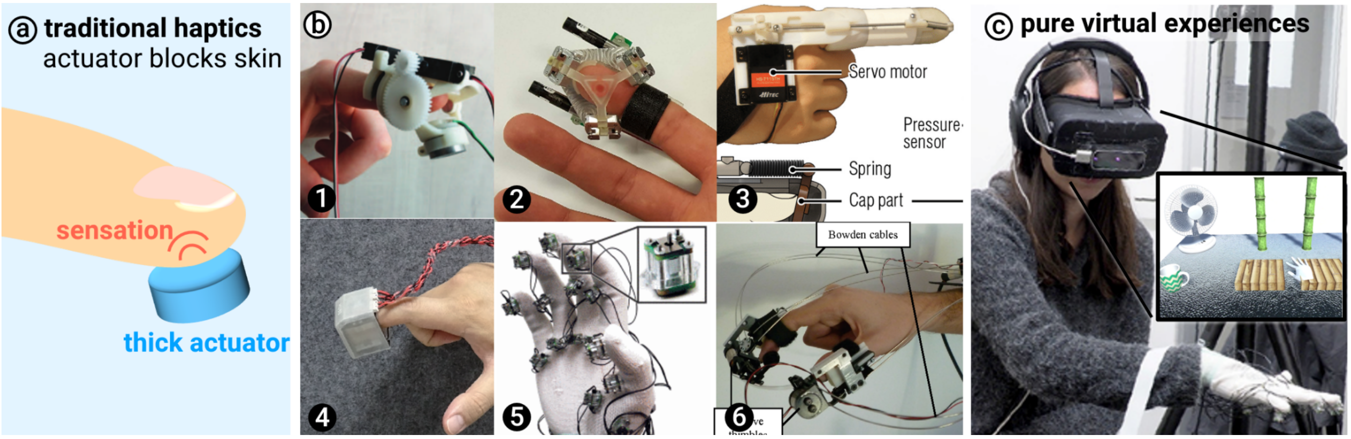

Figure 2: (a) Traditional haptic devices work by placing actuators on a target skin area and directly stimulating it. (b) Examples of haptic devices focusing on generating tactile feedback on the fingertips, mounted with cumbersome mechanical actuators: (1) [47] (2) [140] (3) [82] (4) [94](5) [165] (6) [143] (c) These devices can provide realistic tactile sensations for virtual experiences, such as in VR [165].

with the user's body. While a few prior works have pointed out the problem, no robust argumentation or synthesis of this important issue has been articulated. Thus, we illustrate the problem with the traditional haptics approach with one of the most sought-after and simple examples of immersive experiences: the simple case of a user touching a virtual object in MR.

Conflicts with physical objects (e.g., MR). This problem is particularly interesting in that it is not typically discussed in research: the addition of haptic devices is known to add value to interactions (e.g., especially in VR), but it is rarely discussed how these devices also *remove value* as they diminish the user's abilities to interact with other devices.

MR meetings enable *in-person* and *remote* users to collaborate digitally—examples include holographic teleportation [119], remote collaboration [182], and also commercial endeavors [30]. In these immersive experiences, there has always been a tremendous push and desire towards adding the ability for all users to share not only what they see but also what they feel, i.e., add the sense of touch, so that both remote and in-person users can feel the digital experience. However, as we illustrate in Figure 3 (a), while the current wave of haptic devices allows an in-person user to feel a virtual user (e.g., shake hands with each other [176]), the user's hands are blocked by the haptic actuator, and the user *cannot shake hands* with another collocated user. This situation illustrates what we argue is the main reason why the traditional approach to haptics does not scale for MR: because in MR users spend as much time interacting with virtual objects (which benefit from the addition of haptics) as they spend interacting with physical objects (which are negatively impacted by the traditional approach of adding the haptic actuators at the user's fingerpads). In fact, in Figure 3 (b), we illustrate one more popular example of augmented reality, interior design [5, 120]. In these immersive MR applications, users arrange virtual pieces of furniture in their own living spaces, exploring how they might fit best before purchasing the physical item. While researchers and industry have proposed adding haptics to these experiences so that users can also test and feel the texture, weight, and shape of the virtual object [177], these haptic devices prevent users from comparing these objects with the ones in their physical surroundings. As we illustrate in these two scenarios, the current approach to haptics treats MR haptics as if it were VR haptics.

Conflict with operating other devices. While most researchers take the existing approach as well suited for VR, we bring a user-experience (UX) perspective to this: **users need their dexterity to enter and exit VR** and might, even, need it to use physical tools while in VR—how users will be able to achieve this while their fingerpads are blocked by haptic actuators has been mostly ignored so far. Figure 4 (a) illustrates a user struggling to get into a VR headset while wearing a haptic device on their fingerpads—a situation that readers who tried VR + haptics demonstrations at a conference are familiar with. Moreover, Figure 4 (b) shows that while haptic devices excel at providing haptic sensations for virtual content, they can interfere with other physical devices, e.g., a keyboard for typing, that are also useful in VR [84]. These two examples are particularly striking as mainstream MR/VR experiences (e.g., Meta Quest, HoloLens, Apple Vision) are controlled via finger-based gestures and finger-touch—unsurprisingly, because haptic gloves would interfere with the user's ability to realize these gestures or even put on/off the headsets, the industry has not ventured into providing haptics directly on the fingers/hands for these bare-handed interactions.

Root of these conflicts. Traditional wearable haptic devices stimulate the user's skin underneath their actuators; however, as they do so, they become a barrier preventing the skin from contacting *the real world.* This causes the aforementioned interactive conflicts because humans rely heavily on tactile information for manipulation tasks—as neuroscientists have long established: "To grasp a small object, visual information is essential for accurate reaching (...). Once the object is touched, however. tactile afferent information (...) inside the hand becomes dominant" [3]. This is why even a task as mundane as lighting a match has been shown

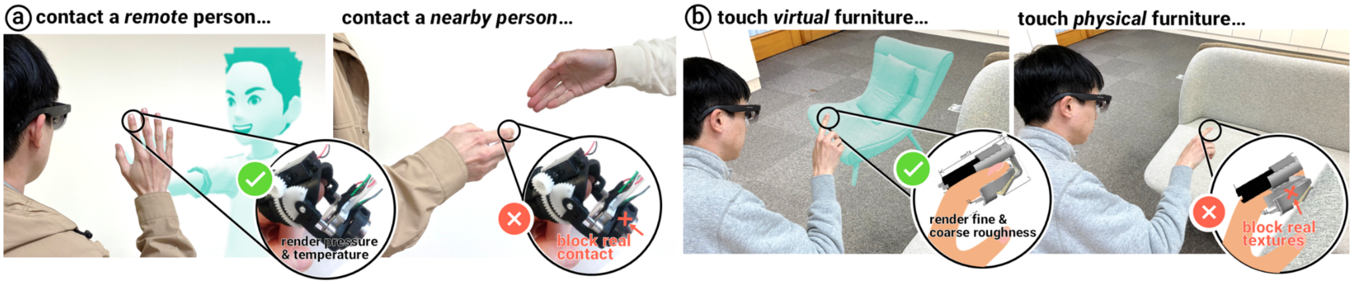

Figure 3: (a) In a Mixed Reality meeting, the user "high-fived" a remote attendee, while wearing a haptic device on their hands to let them feel the touch from the remote person; yet, the same device would block handshaking a collocated attendee (figure adapted from [46] is used to illustrate the concept). (b) In MR interior design, the user can place virtual furniture. While wearing a haptic device, they could feel the textures of the virtual furniture, yet the device would interfere with the physical objects, and thus they could not feel the physical furniture they wished to compare to (figure adapted from [178] is used to illustrate the concept).

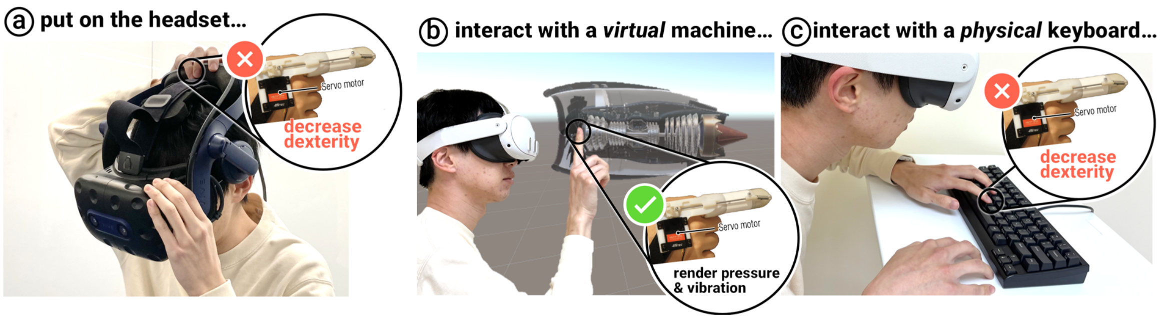

Figure 4: (a) Wearing a haptic device would impair dexterity and make wearing the headset difficult. (b) Wearing a haptic device can provide realistic feelings from simulations (e.g., engine's vibration), yet (c) interacting with a keyboard, the device would interfere. (figure adapted from [82] is used to illustrate the concept)

to be extremely challenging to accomplish without tactile perception [192]. In manual dexterous tasks with real-world objects, our tactile perception allows us to determine, for instance, the ideal forces without letting an object slip or, conversely, without exerting excessive forces that would otherwise damage delicate objects [2]. Moreover, we rely on tactile perception (e.g., vibration, friction, temperature) along with proprioceptive information about ongoing movements to enable tactile exploration (also referred to as *haptic exploration* [89] or *stereognosis* [139]), which contributes significantly to our *material experiences* [28, 74]—even material aspects such as wetness are created from tactile cues (i.e., combination of vibration and temperature [42, 132]). Moreover, tactile perception is also critical to sense danger and enable reflexes (e.g., pain sensation sensed by nociceptors/thermal receptors in the skin [50]). Importantly, it has been demonstrated that wearing gloves or other forms of coverage over one's skin decreases force control and texture recognition [83, 116]. Therefore, donning wearable haptic devices that impede fundamental tactile sensing will affect almost *any interaction* users perform in the real world.

These aforementioned examples are not meant to form an exhaustive list but to show how the majority of haptic wearables are researched and developed under the assumption that they are used in an isolated environment that will not involve any physical objects. We argue that not only has this been wishful thinking from the research community, but it was also never true, as just the act of donning a VR headset requires highly dexterous interactions with physical objects (the headset itself, as illustrated in Figure 4 (a)). These simple examples illustrate that haptics will likely always involve virtual and physical tasks. Given the rise of MR (every major VR headset now ships as an MR device), it is likely to become commonplace to switch between physical and virtual interactions in MR. Unfortunately, only if we solve the way we approach the design of tactile haptic devices can we benefit from these in new territories of MR.

Finally, besides illustrating these examples, we believe a systematic organization would be helpful for the community to understand and classify different approaches to haptics. As such, we synthesize concepts from prior work into a new framework that brings in new factors not always considered when researchers design wearable tactile haptics.

5 Mapping strategies that preserve real-world sensations

Since 2007, Ando et al. [13] proposed a nail-mounted haptic device to augment a surface with haptics, we have gradually witnessed new haptic devices being designed for haptic interactions not only for virtual content, but also for *real-world objects*. Additional examples include Aoki et al.'s string-based haptic device on the fingertip to minimize obstruction [16], Withana et al.'s skin-like haptic device that aims to preserve tactile acuity while wearing the device [174]. These emerging works explored new capabilities that cannot be gauged using existing frameworks for haptics, which often only consider the fidelity of virtual interactions [113]. Furthermore, these works utilize very diverse strategies, from new materials to new mechanisms, each with insights that have never been synthesized together. Therefore, since no cross-paper argumentation has been articulated, it is also difficult to grasp an overview across these different approaches. Thus, we argue that a new high-level perspective is needed that not only focuses on rendering virtual haptics but also emphasizes the importance of preserving haptics from the real world. In this section, we introduce this new framework, which builds on the traditional view of haptic fidelity but expands it into another *orthogonal* axis, i.e., embodying the new direction that focuses on preserving haptic fidelity for the real world.

5.1 Traditional axis: haptic fidelity for the virtual world

From the traditional point of view, an ideal haptic device replicates the haptic sensations of virtual objects that a user expects to feel. As a haptic device increases in fidelity, the rendered sensations better approximate the realism of interacting with the physical counterpart of a virtual object [113]. For example, a virtual object with high-fidelity haptics is expected to provide multiple sensory cues when interacting with it, such as pressure and temperature during contact, or textures when scrubbing. As such, most prior works on haptic devices aim to achieve haptic fidelity using various techniques. We denote this as an axis of "haptic fidelity in the virtual world". This may be seen as a simplified axis for haptic devices, yet it is the most used principle when designing haptics, especially for immersive content. A proof of this is the fact that the widespread way to measure the effectiveness of a haptic device is to ask users to evaluate the *realism*, or properties, of the simulated sensation [98, 140, 165, 170, 177] or to compare the sensations to real counterparts [63, 142].

While high haptic fidelity for virtual objects is worth pursuing (and a very big challenge, as currently no device can replicate all sensations), we argue that this direction *misses critical aspects of the user's experience*. We posit that there is a price to pay for optimizing only on this axis: (1) it neglects the importance of physical objects that the user might want to interact with; and (2) it constrains the range of possible applications for haptic devices (mostly to VR).

5.2 New axis: haptic fidelity in the real world

We argue that a new orthogonal axis should be considered, one that we denote as ***haptic fidelity in the real world***. This axis reflects how well a user, who is donning a wearable haptic device, can perceive and interact with objects in the real world. This notion of *haptic fidelity* includes the ability to feel immediate sensations arising from normal contact with physical objects (e.g., vibration, pressure, deformation, etc.), sensations that arise during haptic exploration (e.g., feeling contours or textures), and even one's dexterity (e.g., the holistic ability to manipulate complex tools and objects).

By proposing this new axis, we (1) highlight an unarticulated goal of a few emergent works, (2) organize these works within high-level strategies, and finally (3) point to future research that can arise from our framework—i.e., the possible research contained in the unexplored space when we consider *both* axes.

5.3 Methodologies for future evaluations

We propose that the haptic fidelity this new axis pertains to can be measured by a variety of methods, from low-level perception studies to high-level application studies—in this section, we exemplify promising directions, but do not attempt to exhaust all possibilities. These study methods can be robustly employed to measure the degree of interference a haptic device imposes on real-world stimuli by contrasting quantitative and/or qualitative metrics captured while wearing a particular haptic device against metrics from a baseline condition (e.g., bare skin or a competing haptic device).

Tactile sensitivity studies. Well-established psychophysics methods in tactile acuity have been utilized in both research and clinical settings to evaluate the tactile sensitivity (e.g., monitoring the recovery after neurosurgery [20, 73]). These include, for among others, the well-known *two-point discrimination*, *grating orientation test*, and *localization* test.

(1) *Two-point discrimination*: Measures the required distance for perceiving two tactile stimuli as spatially separated rather than as a single point. The lower the distance threshold, the higher the perceptual sensitivity; in other words, the higher the tactile "resolution". It is reported that humans can discriminate stimuli that are 2-4 mm apart [32]. In the context of measuring our new axis, this test can meaningfully indicate a loss of sensitivity caused by a haptic device, if the result points to an increase in the discrimination threshold while wearing a particular haptic device.

(2) *Grating orientation*: Measures the ability to detect the orientation of grooves on a surface. To realize it, samples of fine grating (with small grooves) are presented to the user's skin in various orientations (e.g., horizontal, vertical, diagonal, etc), allowing for the characterization of accuracy in perceiving their correct orientation. It is known that humans can discriminate horizontal and vertical gratings (1.5 mm apart) with over 90% accuracy [31]. This test not only can be used to measure this new axis, but has, in fact, already been used in [152] and [174] to quantify losses in perception from thin films that cover up the fingerpad (the latter employed a variant of this test, i.e., tactile ring charts [91]).

(3) *Stimuli localization*: Measures the error between the perceived location of stimuli and their ground truth location. Typically, this is realized by letting users report the location of the stimulus [73] (e.g., verbally, by pointing, by drawing). In in original form, this study was primarily used to map the degree of spatial sensitivity of a skin area (related to the receptive field of that area's tactile receptors [71]). Naturally, it can be appropriated to measure the haptic fidelity pertaining our new axis, by observing any degradation in spatial acuity when users are wearing a particular haptic device.

(4) *Stimuli recognition*: Measures the accuracy of recognizing various predefined stimuli. Typically, this is tested per modalities

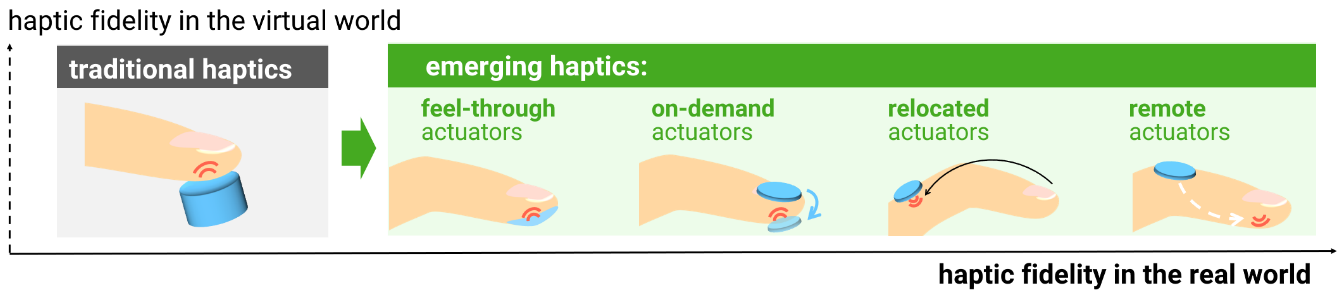

Figure 5: We propose a new axis and a taxonomy of emerging strategies that explore haptic devices in this direction, in contrast to focusing on traditional metrics, i.e., haptic fidelity in the virtual world.

(e.g., temperature, vibrations, textures). Before the test, the user is trained with these stimuli and asked to remember their names. In the test, the user is randomly presented with the stimulus and asked to answer which one is presented (e.g., verbally). This can be used to understand how a haptic device can confuse discrimination, thus lowering the recognition accuracy. One can also find out which stimulus tends to be confused with another in this test (e.g., a confusion matrix). This has been used in [55] to investigate the impact on pressure, vibration, temperature, and texture (bumped points), in [162] to investigate raised patterns, and in [162] to investigate shape patterns.

Object recognition/matching studies. While low-level perception studies provide useful indicators of the impact on tactile receptors, they may not directly imply impact on more elaborate tasks such as recognizing objects through touch (i.e., stereognosis) [65, 81]. While most haptic research leverages low-level sensitivity tests, 3D object recognition is currently less explored—despite its obvious implications to dexterity, which are at the core of what our axis represents.

(1) *Object recognition*: Measures how fast and how accurately a user can recognize an object by touch alone. Typically, objects/shapes (known to the user) are presented for recognition without vision [60], and haptic exploration is encouraged. This test can be adapted to measure our axis's haptic fidelity by noting losses in speed/accuracy while a user is wearing a particular haptic device.

(2) *Object matching:* As with object recognition, this test also measures how well a user recognizes an object by touch, except, in this case, the user performs the task with both hands—one hand is instrumented with the haptic device, while the other hand is left bare-skin as a baseline. Thus, the user is presented with objects on the bare-skin hand while their instrumented hand searches for a matching object. Besides measuring performance quantitatively (i.e., speed and accuracy), it might be fruitful to also elicit qualitative feedback from participants to measure our axis' haptic fidelity, as they are able to rapidly contrast the difference between hands and describe the sensory impairments caused by the device.

Dexterity studies. While the previous methods provide insight into sensations, dexterity tests are useful in determining how devices may affect even more complex tasks requiring precise tactile perception and/or coordination.

(1) *Slip forces:* Measures the forces exerted by a user trying to hold an object as it slips away. These so-called "slipping forces" allow to quantify if a degradation of force control is present (i.e., users have a harder time controlling force precisely due to a tactile impairment) [172]. This is typically measured through a *grasp-and-hold* task, where the user is asked to use minimal force to lift a known weight and hold it. It has been shown that tactile sensations are used for slip control, and blocking/altering tactile sensations correlate with an increase in grasping forces [83]. Not only this can be directly used to measure our axis's haptic fidelity, but it was already employed in [152] to denote that there is an increase in the exerted force (i.e., less precise slip control) when the fingerpads are covered with haptic devices made from thin films.

(2) *Purdue pegboard test*: Measures the ability to fluently manipulate small objects by asking the user to plug pins into pegboards within a given time [9]. The more pins inserted into the pegboard, the more likely the user acted with greater dexterity. It has been used to evaluate dexterity while wearing various gloves [40] and can be adapted to measure our axis's haptic fidelity.

(3) *Joint mobility:* Measures the range of mobility of a joint. This is a particularly well-suited method to measure our axis's haptic fidelity, since joint mobility might be affected when wearing the haptic devices [166]. Thus, it can be leveraged to measure if a particular device obstructs natural movements (i.e., decreased range of joint mobility).

(4) *Finger independence:* Measures how much a finger can move, without causing movement to adjacent fingers. In the typical variant of this method, the user moves a target finger, while any movements induced on the other fingers are recorded [88]. While typically used in the context of force-feedback [115, 145], this method can be readily appropriated in the context of our axis' haptic fidelity, to quantify how much the device constrains dexterous finger movements.

Specific application studies. Beyond low-level studies, it is important to investigate how much these affect the use of specific interactive applications. These studies can reveal important design dimensions. and eliciting qualitative feedback (e.g., how users feel during these interactions [15, 128]).

(1) *Haptic-augmented activities*: We can evaluate haptic devices in the applications they are designed for, especially those that involve interacting with real-world objects, for example, augmenting or modulating the sensations of physical objects or surfaces [66]. For

example, augmenting the boundary on a tablet [10], changing the roughness of the physical surface [27], modulating the softness of a physical button [151]. These are ideal case-studies for measuring our axis's haptic fidelity, since they rely not only on feeling the haptic sensations but also interacting dexterously with real-world objects. One can observe the interactions and collect the subjective feedback from these applications. Besides applications focusing on sensations, prior work has explored haptic guiding applications, such as for needle insertion [135], carving [185], clay making [149]. Since obstructing the physical objects in the applications (e.g., the knife and the wax stick to carve [185]) can strongly affect the outcome, one can measure the performance of these tasks as a metric for our axis's haptic fidelity.

(2) *Usability tests*: Usability tests evaluate how users use a given system. It is widely measured through user observation or usability questionnaires, for example, System Usability Scale (SUS) [93] focuses on ease of use, consistency, confidence, etc. Since we envision haptic devices to work not only for interactions in virtual applications, impeding haptic fidelity can lead to reduced usability in other daily activities. Prior studies were conducted to examine users in office work [174] or walking [23] while wearing haptic devices.

Novel study methodologies. This discussion of possible study methodologies to quantify our axis is, naturally, non-exhaustive as there are countless new methodologies being adopted and experimented with in haptics research. One such example is *micro phenomenology* [57, 129]—a qualitative research method that studies the fine-grained details of lived experience, which relies on guided interviews to help users articulate the rich, subtle, and often unnoticed sensations they experience. In the context of haptics, this method has been used to: explore perceptual qualities of mid-air haptics [35, 117] or to investigate how multiple modalities (visual, auditory, haptic) contribute to the experiences of interacting with data [58]. Just as with micro phenomenology, we expect that other methodologies will be suitable to measure the haptic fidelity pertaining to our axis.

5.4 Strategies in this new axis

To understand the emergence of new work that prioritizes this type of haptic fidelity that this axis proposes, we surveyed the literature, primarily in human-computer interaction, haptics, and robotics. First, all authors of this paper collected prior art manually in a shared database. Additionally, the lead author queried Scopus with keywords "wearable", "haptic", "hands free", "fingerpad free", "unobtrusive", "preserving", "real world", and other synonyms. Results were manually filtered to remove any unrelated work. These sets were manually merged, and any duplicates were removed. Finally, through iterative discussion, we synthesized emergent prior works into strategies of four types:

(1) Feel-through actuator: making haptic devices very thin and conformable allows more tactile sensations from the physical world to be *felt through* when interacting with physical objects (e.g., skin-like actuators).

(2) On-demand actuator: the haptic actuator stimulates the target skin area *on demand* during virtual interactions and retracts to avoid obstruction if the target skin area needs to be free for feeling physical objects (e.g., foldable actuators).

(3) Relocated actuator: *relocating* the haptic actuator to other body parts allows the device to entirely avoid obstructing the target skin area (e.g., relocating a haptic device that represents finger touches to the wrist).

(4) Remote actuator: this leverages a transmission mechanism to *remotely* deliver a haptic sensation to the target skin area from the vantage point of another, non-obstructed, body location (e.g., using a focused vibrational wave).

In the following, we elaborate on these strategies by discussing the emergent research that led to each category and, importantly, defining its key terminology.

6 STRATEGY #1: Feel-through actuator

Definition. This strategy preserves the haptic sensations from the real world by making the actuator as thin and as conformable as possible, depicted in Figure 6 (a). This allows more transmission of haptic sensations when touching physical objects and also preserves the user's dexterity. The ultimate goal is to literally *feel through* by using wearables so soft and thin that they are mechanically imperceptible; yet they can produce sufficient sensation when actuated to make virtual objects feel real or to overlay sensations over the surface of real objects.

6.1 Current state of feel-through actuators

Researchers have explored thinning various kinds of haptic actuators, which include mainly mechanical and electrical actuators. Exemplar devices and applications are shown in Figure 6 (b)(c). We describe the current development to date briefly, while a more in-depth discussion of feel-through actuators can be found in [75].

Mechanical actuation. Traditional vibration motors (e.g., ERM or LRA) are rigid and too cumbersome for the user to feel through the device. Researchers developed new types of actuators that are soft and thin [22], including fabric actuators [41], string actuators [17, 175], microfluidic actuators [54, 56], magnetic actuators [103, 188], dielectric elastomers [85, 183], piezoelectric actuators [69, 190], and resistive heaters [171]. For example, Hydro Ring [54] presented a ring worn on the fingerpad that uses pumped water to create a sensation of pressure, vibration, and temperature; yet the relatively low thickness (100 μm) of the ring resulted in an unobtrusive device that could be used in XR. Actuators like electroactive polymers can be made extremely thin (18 μm) to achieve forces in a feel-through form factor [67]. Similarly, wire-based actuators were also designed to minimize interference with the fingerpad, but in their current form, these provide a limited haptic contact area [17].

Electrotactile actuation. Given that electrodes can be made smaller than a mechanical actuator (which requires physical displacement and extra volume), electrotactile devices can be made into dense arrays, suitable for the fingerpad [1, 76, 77, 86]. Electrotactile actuators are leveraged to deliver textures [49], shapes [137], and even softness [179]. By injecting current into the skin through electrodes, electrotactile feedback can be provided in a thin elastomeric tube (500 μm) [181] or even through a tattoo paper [174] that is only 35 μm thick.

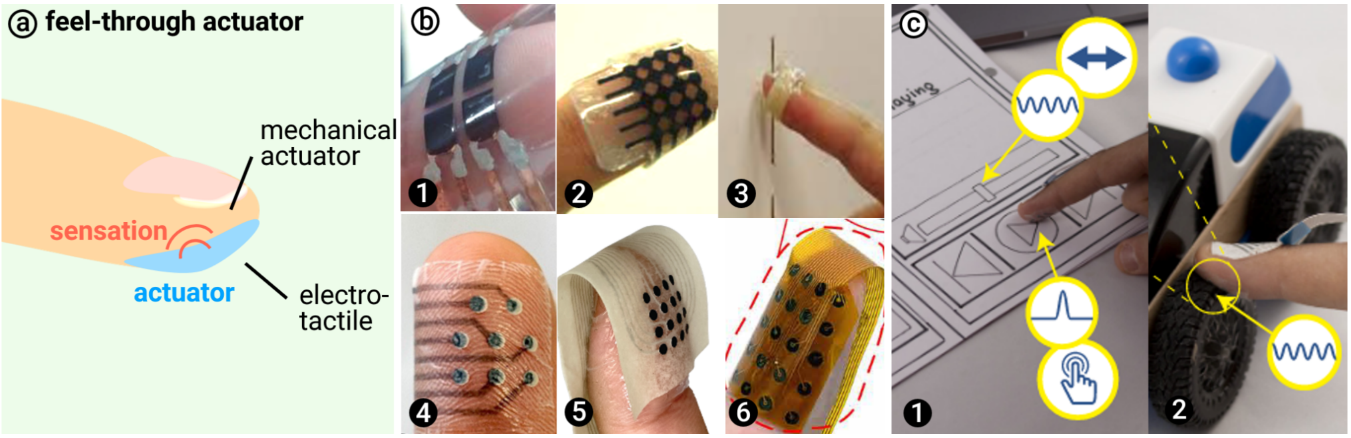

Figure 6: (a) Feel-through actuators are haptic actuators that are made very thin and conformable, with the goal of letting more stimuli from the physical world go through. This can be done mechanically using flexible materials, or through electrotactile with thin electrodes. (b) (1) Flexible vibration array [147] (2) Soft actuators [85] (3) HydroRing [54] (4) Tacttoo [174] (5) Pixelate [148] (6) High-resolution electrotactile array [96]; (c) Example applications from [174]: (1) the user can feel the paper being augmented with haptic feedback (2) the user can feel both the texture of the tire and the vibration from the device.

However, a downside of this strategy is that, when applied to haptics targeting hands/fingers, it results in devices implemented in a glove form-factor. Unfortunately, researchers have confirmed that even thin films impair tactile perception in roughness [116]. For instance, wearing thin gloves such as the ones used in dental work has been shown to decrease force perception and dampen vibrations [39, 189]. Similarly, the required grasping force increases in a lift-and-hold task while wearing gloves [83].

6.2 Design considerations for feel-through actuators

Towards higher resolution. Feel-through actuators cover the target skin directly (e.g., the fingerpad) and can provide direct stimulus when touching virtual objects. Micro-actuators can be packed as arrays onto the device to provide high-resolution haptics at precise locations, which enables the rendering of fine features (e.g., Braille), realistic textures, and precise change of skin contact area for softness perception.

Increase rendered submodalities. Most of the feel-through devices can only render one kind of haptic feedback (e.g., electrotactile, thermal feedback). To increase the number of modalities, one can intertwine different actuators to an array by trading off some resolution, or stack various thin films in a configuration that can still deliver multiple sensations onto the skin [63]. Stronger forces or forces that deform the fingerpad can be more difficult to make thin and conformable; yet researchers have looked into utilizing cutaneous feedback to create illusions of such forces, like weight [95].

Even more feel-through. Thin devices are shown to improve tactile sensitivity, e.g., 2.5 μm device provides 47% improvement in spatial acuity compared to 390 μm devices [116]. However, while users of HydroRing can still dexterously interact with the world much like wearing a latex glove, even *100 μm thickness can be thick enough to impede feeling real object surface characteristics* (e.g., texture, friction, vibration, precise pressures) through the device [116]. Commonly used tattoo paper (35 μm) on the fingerpad is shown to result in a 30% increase in the sensitivity threshold compared to bare fingerpads [116] (i.e., making the skin less sensitive). Mechanical soft actuators are difficult to make thinner while still being able to generate feelable sensations, due to low-force densities of thinner materials. Moreover, typical soft actuators based on fluid-pressure generally undergo volume/thickness changes when actuated, creating further variability in their impact on feeling the real world. Besides making devices thinner, researchers have explored how revealing part of the fingerpads, e.g., holes, can increase the perception and further increase dexterity in real-world tasks [51, 152].

Durability. A byproduct of creating softer and thinner devices is a reduction in the long-term durability of the device, especially in the case of feel-through haptics, where thin films are dragged along rough, real-world surfaces. This challenge will require carefully balancing the device's rigidity with its durability (e.g., tested in daily activities [174]). Moreover, initial research by Nittala et al. surprisingly found that thin epidermal devices based on PDMS with a hundred times the rigidity of commonly used tattoo paper resulted in comparable levels of tactile acuity despite rigidity differences [116]. Therefore, a better psychophysical understanding of the interplay between rigidity and other perceptual factors is needed.

7 STRATEGY #2: On-demand Actuator

Definition. This strategy avoids blocking the target skin area by using *on-demand* actuators that can retract when not in use, as depicted in Figure 7 (a). The haptic actuator only comes in contact with the target area when haptics need to be rendered. The device in its compact form is then placed at a body part that would be adequate for permanently mounting without impacting interactions (e.g., potentially the wrist, nails, and more), leaving the critical part of the body part free of the device by default. This idea can be

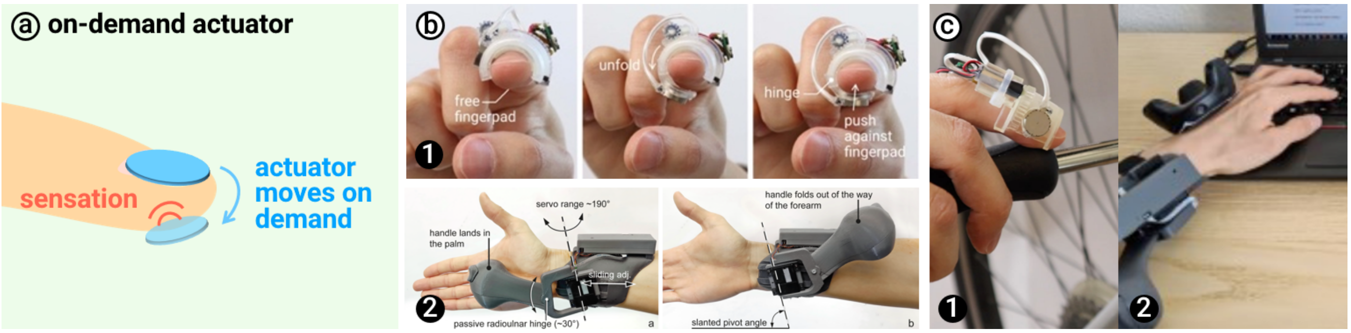

Figure 7: (a) On-demand actuators move actuators to the target body part to create sensations. (b) (1) Touch&fold [154]; (2) Haptic Pivot [87]. (c) Example applications: (1) revealed fingerpad allows the user to manipulate a screwdriver with high dexterity; and (2) without obstructing the hands, the user can type on physical keyboards when not interacting with virtual interfaces.

seen as a robotic approach to minimize instrumentation and its obstruction.

7.1 Current state of on-demand actuators

On-demand actuators can be categorized by different mounting locations. Exemplar devices and applications are shown in Figure 7 (b)(c). Touch&Fold [154] is a nail-mounted haptic device that keeps the fingerpad free by default; when the user touches virtual objects, the device slides down a cover (with vibration motor) to create contact with the fingerpad to generate the sense of touch. The device tucks away (folded back to the nail) prior to the user grabbing physical objects, e.g., a tool. The mechanism (rack & pinion) takes up to 92 ms to switch between states. By having an actuator brought to the fingerpad to render haptics, more modalities that require bigger actuators, such as pressure, vibration, and temperature, can be possible. FingerX [158] utilized a similar mechanism but extended the concept with extruded structures, enabling rendering shapes in combination with existing physical objects. Besides the fingers, the palm is another site that has great potential for on-demand actuators since the wrist is a convenient place to mount actuators. Haptic Pivot [87] and WeATaViX [156] both focus on providing feedback for the whole palmar side by moving a ball-shaped end-effector from the forearm to the palm through a hinge. The full hands can be left free of devices when not in use, such as when typing on a physical keyboard. Researchers further explored rendering finer-grained forces on the palm [70]. Recently, we have seen early explorations in industry along this strategy, such as FlipVR [43]—a pair of wearable controllers that can be folded away through passive hinges when the user interacts with physical objects. Their commercial demonstrations showcased interactions switching between virtual and physical interactions (playing musical instruments). The concept of on-demand actuators can be seen as closely related to *encounter-type* haptic devices [106]. Encounter-type haptic devices are those that "position a tangible surface for the user to encounter", often realized through external robots such as a tabletop robotic arm [18], while some are mounted on the user's body, e.g., torso [8]. While these can be thought of as encounter-type haptics, the majority of encounter-type haptics do not directly aim to preserve real-world interaction. In the context of this paper, we use the term on-demand actuators, which are described more from the user's perspective on how haptics is delivered according to needs (i.e., device can come and go).

7.2 Design considerations for on-demand actuators

Less cumbersome mechanism. In these devices, a mechanism is required to be mounted on another body part, and this still takes up space and can interfere with the user's mobility (e.g., manual dexterity). It is worth investigating whether this tradeoff is acceptable in many tasks. Miniaturization of the mechanism can push forward this strategy, but it can be challenging. Furthermore, the mechanism determines the workspace of the actuators, i.e., the available area where the mechanism can reach, which becomes the area where the haptic actuators can render feedback. This can lead to tradeoffs between size and degrees of freedom, e.g., a longer structure (thus larger) may be needed if the distance to the target location is far. Furthermore, most examples of on-demand actuators utilize rigid mechanisms, which can be uncomfortable as wearable devices. HapWRAP utilized inflatable actuators to dynamically wrap around the forearm as a way to render feedback [4]. Exploration with other soft mechanisms or other minimal mechanisms (e.g., leveraging origami [173]) can extend the practicality of such a strategy.

Response time. These approaches are mechanical in nature, which implies that they require substantial time to physically move in and out of position (340ms for [87] and 92ms for [154]), especially when compared to the remaining strategies discussed in our framework, which do not add significant latencies in their realization. This can be a hard constraint for many haptic applications that require responsive feedback of a few milliseconds.

Incorporate a wide range of actuators. The advantage of this approach is that the actuator can be placed elsewhere, ideally a place that is more tolerant of mounting (e.g., wrist). Thus, the haptic sensation can be less limited by the size and rigidity inherited by their actuators, as long as they can be retracted back into the device. Stronger and more diverse haptic actuators, such as Peltier elements for heating, may be integrated onto the device.

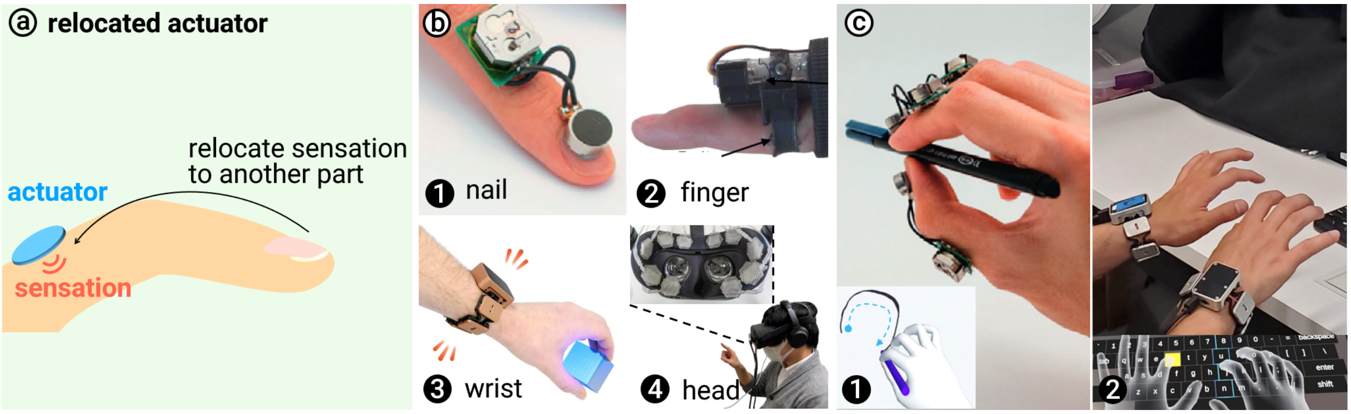

Figure 8: (a) Relocated actuators provide feedback to a different part of the body than the target skin (fingerpad), keeping it entirely unobstructed from the device. (b) (1)Haplet [128]; (2) Tinguy et al. [157]; (3) Tasbi [126]; & (4) Haptopus [78]. (c) (1) Drawing in VR using a physical stylus while wearing the actuators on the back of the fingers [128]; (2) Typing on a virtual keyboard with Tasbi [52].

8 STRATEGY #3: Relocated Actuator

Definition. This strategy lets the fingerpad be entirely free during interactions by *relocating* the haptic device to a different part of the body, as depicted in Figure 8 (a). In this case, a haptic device delivers a sensation that represents virtual touch on the fingerpad, but delivers the sensation to a different patch of the skin—often denoted as *relocated haptics* [11, 109] (or *distal* as seen in literature [104, 155]). The underlying concept is that, albeit the fact that the sensation might not be felt at the correct location, by appropriating the timing and modality of feedback, relocated actuators can still reduce the visuo-tactile mismatch at the target location [126], while keeping it free. This concept is inspired by practices in the field of prosthetics, where mechanical pressures or vibrations applied to body parts of amputees represent haptic sensations that should be felt in their missing limbs [14].

8.1 Current state of relocated actuators

Relocated actuators map haptic feedback from the fingerpad to various parts of the body, ranging from areas as close as the fingernail to as distant as the forehead or the back. Exemplar devices and applications are shown in Figure 8 (b)(c). We provide a succinct description of the work, focusing on those that aim to preserve real-world haptics (a more in-depth review on haptic relocation can be found at [134]).

Actuators placed on the fingernail or the sides of the fingerpad can create the sensation within the same finger as the target fingerpad, minimizing the mismatch in location of haptic sensation. For instance, nail-mounted vibrotactile actuators can represent contact with the virtual object [9] and numerical characters [59], or augment texture sensations while touching a physical surface, as demonstrated by Ando et al. [11]. A similar texture augmentation is also possible via skin-stretch feedback applied to the sides of the finger [99]. The side of fingers has attracted attention for attaching devices, including electrodes for electrotactile [6, 68, 114], thermal actuators [136], and devices that deform the fingerpad for perceptual force sensation [187]. Vibrations applied to the proximal end of the finger [45] can also augment the sensation for textures. Having an actuator at the proximal end of the finger can accommodate a relatively bulkier device, enabling mechanical pressure and squeezing feedback [133, 157]. To leave the entire hand hardware-free, some relocated actuators map haptic sensations to the user's wrist; much of the prior work has explored the application of mechanical pressures to the wrist through devices such as a wristband [126] or linkage mechanisms [110, 122]. A study has demonstrated that haptic feedback from such a wristband device can communicate the contact and perceived stiffness of virtual objects when the feedback is presented in conjunction with visual cues [127]. Beyond the hand, McAdam and Brewster explored providing feedback to various parts of the body (including chest, waist, etc) through vibrotactile actuators [104, 155]. Conceptually, relocated actuators can be positioned on any part of the body other than the fingerpad, or even multiple parts of the body; for example, FEEL TECH Wear [161] relocates fingerpad sensations to the nails for vibrations and the wrist for skin-stretch. There are devices that relocate haptic feedback to locations extremely distant from the fingerpad. For instance, Kameoka et al. demonstrated that the suction force applied to the user's forehead through pneumatic actuators integrated into a VR headset could modulate the perceived stiffness of virtual objects touched by the fingerpad [78]. Moving further away from the fingerpad also allows feedback from a relocated actuator to be mapped to a much larger skin area. For example, Moriyama et al. demonstrated a vest device that transfers haptic feedback from the fingerpad to the user's back via 144 vibrotactile actuators [111].

8.2 Design considerations for relocated actuators

Integration into physical tasks. As this strategy avoids target location entirely, haptic feedback can be effectively delivered in most real-world scenarios that involve diverse physical tasks (compared to the aforementioned strategies), such as assisted palpation with a robotic surgery device to lower force error [169] or augmenting physical props for training [133]. This has been proven useful for

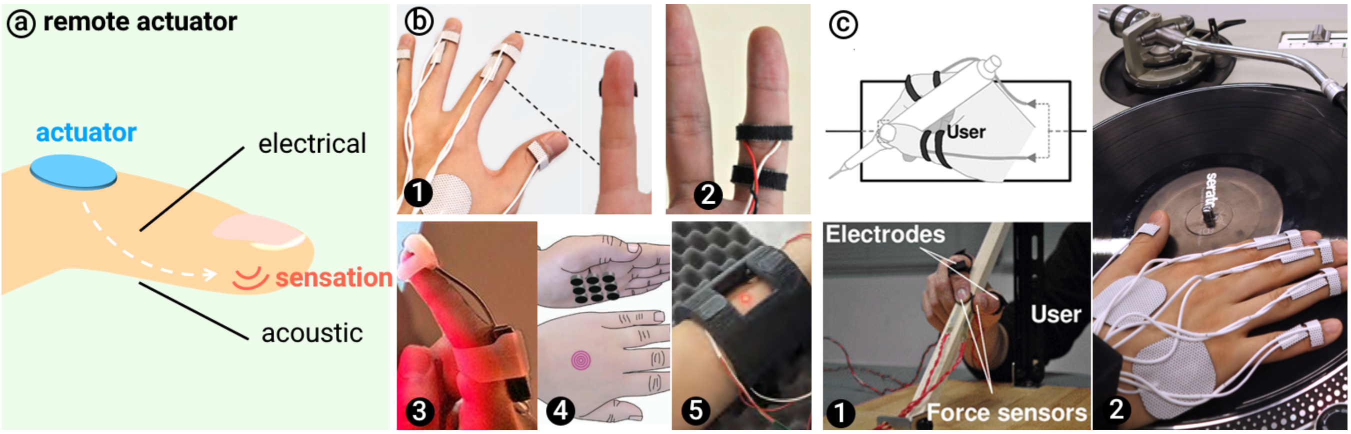

Figure 9: (a) Remote actuators create sensations in a target while actuators sit on another patch of skin. (b) (1) [149] (2) [186] (3) [79] (4) [144] (5) [167]; (c) Examples: (1) tactile sensations on physical objects, such as tools [184]; (2) DJ guidance on a turntable [149].

rendering symbolic representations, e.g., presenting directions for rowing training [131].

Shift in perceived sensation. Because the location of the haptic stimulus is not co-located with its intended location (e.g., a virtual sensation on one's finger is now rendered to one's wrist), users may need to learn and accept this *mapping*. Some research has shown that visual feedback can increase the sense of realism of mismatched expected-to-stimulated locations [150]. Mapping may not be trivial as the sensitivity and resolution of haptic sensations vary across our body (e.g., the finger's acuity is far superior to the wrist, and so forth). Most prior work only focused on single actuation—used for general-purpose interface feedback—rather than high-fidelity haptic rendering, e.g., texture rendering or multi-point shape rendering. As the sensations for the real and the virtual are different, this strategy may be more suited for general types of feedback (e.g., confirmation cues), but not certain applications that require a 1-1 mapping from the virtual to the real world (e.g., simulated training for physical skills may require using the exact same part of the body to perceive haptic feedback—otherwise, users might not learn the actual corresponding sensations of the skill).

Design for different sensitivities. The tactile sensitivity of each submodality and its spatial acuity vary across body parts. When designing for relocated actuators, one must consider such when translating denser and richer sensations that a user can perceive (e.g., from the fingerpads) to where they are less sensitive (e.g., the wrist). Researchers have designed interactions for multi-scale haptics in textile-based actuators [191]. Similarly, it is worth investigating how we might utilize the advantages of relocation to different body parts. FEEL TECH Wear [161] is an example of separating submodalities into two parts: vibration relocated to the nail and skin-stretch feedback relocated to the wrist.

9 STRATEGY #4 Remote Actuator

Definition. The haptic actuators create sensations in a *remote* patch of the skin while they sit on another patch of skin, as depicted in Figure 9 (a). Importantly, unlike relocated actuators, this approach stimulates the intended target, i.e., the desired area is where the sensations are felt. This is typically achieved by using a transmission method that is compatible with the human body, which allows for inducing a remote sensation from the place where the actuator is placed (i.e., also denoted as *referred sensations* [105].)

9.1 Current state of remote actuators

Remote actuators have been explored primarily through focused vibration waves or electrical stimulation. Exemplar devices and applications are shown in Figure 9 (b)(c):

Remote vibrotactile sensations. Since vibrations are mechanical waves that propagate under the skin, they can exhibit phenomena such as constructive, destructive, and reflective interference, which can affect the intensity or location at which vibrations are felt. One may utilize these effects to "send" vibrations to a remote location. Keller et al.'s patent [81] describes a concept that combines signals originating from several transducers at the wrist/forearm to elicit haptic sensations at remote locations such as fingerpads—enabling the fingerpad to be free, yet receive haptic feedback. In research, it has been shown that interference sensations can be created between multiple vibration motors mounted on the fingertip [19, 107] or on the hand [24]. Dandu et al. demonstrated that vibrotactile stimuli directly applied to the fingertip can cause tactile sensations in the middle phalanx, the proximal phalanx (finger base), or the whole finger via constructive interference of the vibrations propagating through the finger [36, 37]. While this shows the fundamental insights and the potential of the approach, the device itself covers up the fingerpad. Tactile Echoes [80] investigates the propagation of vibration on the finger with the device mounted away from the fingertip to augment sensations of various physical materials, yet the vibration would be felt on all parts of the finger. Thus far, the work closest to the aforementioned ideal vision is SkinHaptics [144], which is able to cause tactile sensations in the palm via constructive interference of ultrasound vibrations applied to the back of the hand. Yet, it is still unable to target a specific localized region in the palm, let alone the fingerpad. To improve the spatial resolution of the approach, Vlam et al. recently proposed a filter technique that computes and corrects the delays and amplification of different vibration actuators and demonstrated its feasibility to create sharp localized tactile sensations in the palmar-side forearm via four actuators surrounding it [167].

Referred electrical sensations. Electrical currents can cause sensations in mechanoreceptors, even in those distant from the stimulated point [108]. This has been primarily explored in prosthetics to provide tactile feedback to the prosthetics [29, 97, 124]. Recently, neuroscientists started investigating this phenomenon in subjects with intact limbs, and reported that tactile sensations were evoked on the hand through electrical stimulation at the forearm [48, 138], elbow [44], and arm [164]. Specifically, Alonzo et al. showed that stimulating the lower palm could evoke sensations in the fingers [7]. Moreover, this can also be built into interactive haptic devices. Yoshimoto et al. used it by attaching a pair of electrodes to the root of the finger, on the palmar side, to cause a tactile sensation at the fingerpad [184, 186]. Tanaka et al. uncovered the palmar side of the hand by moving all the electrodes to the back of the hand and demonstrated rendering tactile sensations at 11 points on the palmar side, including fingerpads [149]. On the contrary, Ogihara et al. explored an approach to render tactile sensations in the hand only via an array of electrodes at the user's wrist [118]. While their approach did not induce precise tactile sensations on the fingerpads, they demonstrated causing sensations at multiple locations by switching the electrodes being used for the stimulation.

9.2 Design considerations for remote actuators

Pose sensitive. Many of these works are tested under stable conditions and are sensitive to poses. Vibration propagation is determined by the biomechanical structure of the body. Therefore, any changes, such as pose or contraction of muscles, may affect the body's physical properties, thus changing how vibration may be focused. Electrotactile approaches also are not pose invariant, due to the electricity paths changing when tissues are stretched, or simply when the skin and the underlying tissues are shifted. This is a difficult challenge for this strategy, and future work may investigate precise sensing for more robust rendering.

Calibration. Most of these techniques require intensive calibration, as individual differences play a big role. Often time calibration is conducted by experimenters as it is not trivial for the users to calibrate. Even if well-calibrated, this calibration may fail when the user moves their hand, and thus, more specific online calibration should be required for rendering robust sensations [163]. Despite remote actuators being an exciting strategy, they can lead to very unpredictable haptic rendering in practical scenarios.

Balancing spatial acuity and dexterity. While remotely causing haptic sensations with the hand unobstructed, remote actuators compromise the spatial accuracy of the feedback. This is because remote actuation relies on stimuli traversing the inside of tissue (i.e., vibration or electrical currents); as devices can only determine the input stimuli at the remote patch of the skin, they are unable to precisely control how the stimuli reach the receptors innervating the target patch of the skin. For instance, electro-tactile feedback via the wrist can render tactile sensation at the fingerpad while also causing side-effect sensations at the rest of the finger or even the palm [118]. It is possible to be specific to the fingerpad by moving the electrodes to the back of the hand [149] or the root of the finger [184], but such moves compromise the originally preserved manual dexterity (i.e., the whole hand free vs. only the palmar side free). Here, we see the trade-off between preserving the spatial matching of feedback and how much of the hand is kept free. As shown in prior work, the limitation of referred sensations via electrical stimulation is that it loses spatial accuracy as the positions of electrodes get farther from target areas; attaching the electrodes to the back of the hand renders the sensations on different finger segments including fingerpads [149], whereas the stimulation to the wrist cannot isolate the sensations on the palm from those on the fingers [118]. This leads to a key trade-off between the tactile acuity of virtual and physical objects that designers should be aware of.

10 Discussion and outlook

Having presented a novel taxonomy to classify these emergent strategies for haptics that preserve haptic fidelity in the real world (the novel axis our framework adds), we summarize them by comparing their impact in both the virtual and the real world to reveal their pros & cons. While we will not present a set of qualitative assessments, as all of these devices are in their early stages, we focus on comparing their idiosyncratic challenges. We believe this overview is beneficial for researchers and designers to explore the various tradeoffs and assist with choosing an approach for applications.

10.1 How pros/cons affect the potential applications of each strategy

Compared to traditional haptic devices, leveraging these strategies (i.e., feel-through, on-demand, relocated, remote) allows us to preserve more haptic fidelity from interactions with the real world. We synthesize the results from these works and present their high-level performance in virtual and real-world haptics and suitable applications:

Feel-through actuators render high-resolution but block the skin: Since the actuators make contact with the target skin (i.e., fingerpad) at all times, which is also one of the most sensitive parts of the body, they are most suitable for displaying high-resolution patterns (e.g., textures, Braille). However, since the device must be very thin, this limits the range of submodalities that can be available at the same time (e.g., skin-stretch feedback requiring more sophisticated mechanisms challenging to make thinner). Nevertheless, even with a thin layer covering the skin, it inevitably decreases dexterity in the real world. While manipulating certain tools may not be a problem, especially for tasks that already require wearing gloves (e.g., low-load work such as using surgical tools), using feel-through actuators for daily life may be challenging, as one can no longer feel the original textures of daily objects (roughness can be altered with even very thin devices).

On-demand actuators avoid obstruction, at the expense of other obstructions: This strategy brings the actuators when needed, creating sensations that can be more natural, e.g., stronger pressure and vibration. These are useful to present multiple submodalities at the same time, such as rendering material properties of a wider range (e.g., approximate shape, impact). This strategy leaves the target skin free, which preserves the natural tactile acuity. However, the mechanisms take up a large volume of space and may impair limb movements—across all techniques, this is, logically speaking, the one with the largest physical footprint: i.e., it requires one actuator (which all other techniques do as well) *plus* an additional mechanism for on-demand delivery. As such, these devices may be challenging if the application requires extreme dexterity or empty space around the location where the actuator is stored when not in demand. For instance, on-demand actuators on the fingers may be suitable for applications that do not require close or cross-finger movements; similarly, those mounted on the wrist may not be suitable for bimanual tasks.

Relocated actuators avoid obstruction but limit realism: This strategy frees itself of the constraint of existing on the target skin area and can offer stable feedback, which has started to attract the industry's interest [126]. However, this strategy sacrifices the realism of virtual haptics, and the sensation itself may not be natural and requires learning, i.e., users must understand the mapping between expected-location and felt-location. While this strategy can be powerful for general feedback (e.g., confirmation feedback for selection, etc. [123]), it may be challenging to render complex real-world sensations, such as shapes, textures, etc. Additionally, since sensations are felt in an "unnatural" area, this technique may not be challenging for virtual training that is hoped to transfer skills from virtual interactions to real-world tasks.

Remote actuators avoid obstruction, yet the effect is less predictable. Remote actuators inherit the benefits of relocated actuators with the additional benefit of remotely delivering sensations closer to the expected location. In this light, applications such as simulated training may be more suitable (when compared to relocated actuators). However, based on their physical transmission principles (e.g., focused vibration propagation or nervous system interception), these techniques demand intense calibration procedures and are not entirely pose-invariant (e.g., if the user's body changes, the propagation of these signals can change and affect the resulting stimulation area). As such, as the most emergent class of strategies, these are likely to require solving major challenges before their potential application areas are reached.

10.2 Future research directions

Despite the initial key innovations that kickstarted each strategy, challenges remain—particularly as the demand for more immersive, intuitive, and versatile haptic devices grows across newly established domains, namely XR, haptic-centered smartwatches [126, 146], or even more nascent screenless haptic interfaces (e.g., sensory substitution [38, 153]).

To continue advancing the state of the art, we provide a potential roadmap for this area. Our aim is to synthesize and outline several key directions for future research that are crucial for pushing the boundaries of multimodal interactions.

Tipping the balance between real/virtual. While these emergent works aim to preserve more haptics in the real world, they do so at the expense of interactive trade-offs (e.g., sacrificing realism for virtual haptics). It is worth investigating what kind of trade-offs might be acceptable and what different types of "sweet spot" exist for balancing between the fidelity of both the virtual and the real world. We expect that as future research explores how these devices can support ever more complex activities (e.g., skill training and transfer), this will lead to deeper understandings of the inherent trade-offs that arise from each strategy.

Direct comparisons across strategies. These emergent strategies were evaluated differently in each work. A direct comparison of these strategies is an important and much-needed next step that is required to investigate their impact on perception and interaction more holistically. This will also shed light on any possible generalizations across strategies.

Long-term/outside-the-lab evaluations. Regardless of the method used for evaluation, most haptics research is typically evaluated through short-term in-lab studies. Thus, as haptic devices move into the real world, it becomes paramount to explore them both outside the lab and in longitudinal studies. This might shed light on environmental/social factors (e.g., ambient haptics, social acceptance) and the inherent long-term limitations of each device (e.g., durability, comfort)—to this end, the methods discussed in Section 5.3 may provide a future roadmap.

Expand to more haptic modalities. One can take an under-explored sensation (e.g., temperature, skin deformation) and seek strategies that realize this sensation while preserving haptic fidelity in the real world. This may require searching for novel actuators, leveraging perceptual illusions, novel interaction designs (e.g., mappings), and investigating side effects. Ideally, any sensation that a device supports should be implemented in a way that makes it possible to generate more sensations (e.g., possible approaches include interweaving actuators, rather than stacking, to keep the device thin).

Combining strategies. One can imagine that not only one strategy may be used, but a combination of them. For example, on-demand actuators can be combined with relocated actuators (i.e., depending on the task, haptics can be delivered through either actuator); or, feel-through actuators may be combined with remote actuators (i.e., enabling haptics on site or remotely—covering a wider stimulation area). Importantly, for future research in this space, the integration of multiple strategies in the same device might allow for circumventing the inherent limitations of each strategy.

Interdisciplinary research. Furthermore, this roadmap emphasizes the importance of interdisciplinary collaboration between researchers in different areas such as robotics, neuroscience, material science, and human-computer interaction. As these emergent haptic strategies prove, progress in one area can often spur innovation in others. For instance, advances in decades of material science enabled HCI researchers to explore the benefits of thinner materials and gave rise to the "feel through" strategy. Similarly, advances in robotics might have seeded the mechanisms needed to realize on-demand actuators; research in prosthetics might have inspired relocated actuators. Finally, insights from neuroscience, such as referred sensations, provided a solid foundation for innovations in remote actuators. As such, we call for efforts to create haptic interfaces across disciplines.

Bridge to industry. Finally, we emphasize the importance of collaboration not just across disciplines of research, but also with industry. While research often lays the theoretical groundwork to push the boundaries of fundamental science, industry provides real-world application and the manufacturing capabilities that are crucial for translating these ideas into practical, scalable interfaces—as exemplified with the case of XR headsets. Similarly, industrial efforts have enabled the commercialization of soft materials & actuators initially developed in academic labs. To fully explore these emergent haptic strategies, especially towards future mainstream uses, it is crucial that both sectors work together closely.

11 Conclusions

Traditional haptic devices have largely focused on improving the sensation of virtual interactions, but rarely considered the fact that users also need to feel physical objects. We see that this has led to most haptic devices being impractical to use outside of VR and teleoperation scenarios. We argue that haptic fidelity in the virtual world should not be the only axis for optimization and propose that researchers & practitioners should also optimize the fidelity of real-world sensations. We see that works in the last 20 years have emerged to counter the traditional goal of haptics and are motivated by designing for new interactions in the real world. While these seemingly use different types of techniques, we believe they share similar goals that can be synthesized into strategies, including feel-through, on-demand, relocated, and remote actuators. We hope that this paper highlights an important emerging direction and inspires researchers to envision balanced future interactions between the virtual and the real worlds. Finally, we provide not only a taxonomy of these novel strategies, but a discussion of possible evaluation methods, and important future challenges.

12 Use of AI in this paper

No Generative-AI systems were used in writing this paper, nor in developing our argument.

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